LARGE SCALE MAPPING OBSERVATIONS OF THE CI ($^3P_1 -^3 P_0$) AND CO ($J = 3 - 2$) LINES TOWARD THE ORION A MOLECULAR CLOUD

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ABSTRACT

Large scale mapping observations of the ${}^3P_1$–${}^3P_0$ fine structure transition of atomic carbon (CI, 492 GHz) and the J=3-2 transition of CO (346 GHz) toward the Orion A molecular cloud have been carried out with the Mt. Fuji submillimeter-wave telescope. The observations cover 9 square degrees, and include the Orion nebula M42 and the L1641 dark cloud complex. The CI emission extends over almost the entire region of the Orion A cloud and is surprisingly similar to that of ^{13}CO(J=1-0). The CO(J=3-2) emission shows a more featureless and extended distribution than CI. The CI/CO(J=3-2) integrated intensity ratio shows a spatial gradient running from the north (0.10) to the south (1.2) of the Orion A cloud, which we interpret as a consequence of the temperature gradient. On the other hand, the CI/^{13}CO(J=1-0) intensity ratio shows no systematic gradient. We have found a good correlation between the CI and ^{13}CO(J=1-0) intensities over the Orion A cloud. This result is discussed on the basis of photodissociation region models.

Subject headings: ISM: atoms, ISM: molecules, ISM: individual(Orion A)

1. Introduction

Neutral atomic carbon (CI) plays important roles in cooling and chemical processes in interstellar clouds, and its submillimeter-wave transitions (${}^3P_1$–${}^3P_0$, 492 GHz; ${}^3P_2$–${}^3P_1$, 809 GHz) have been observed toward various objects. The detailed distribution of CI around representative objects including photodissociation regions (PDR) has been studied at high angular resolution (e.g., Minchin et al. 1994; Tauber et al. 1995; White and Sandell

1995). Since CI is widely distributed throughout our Galaxy according to the data from the COBE satellite (Wright et al. 1991), it is of fundamental importance to map its large scale distribution over molecular clouds. Pioneering studies in this direction have been made using a focal reducer installed on the CSO 10 m antenna (Plume et al. 1994, 1999; Tatematsu et al. 1999), to survey the distribution of CI toward several molecular clouds with a moderate resolution of $\sim 3'$. In spite of these efforts, the observed areas are still limited relative to available maps of CO and its isotopomers. With this in mind, we have recently constructed a 1.2 m submillimeter-wave telescope for the exclusive use of CI survey observations at the summit of Mt. Fuji.

The Orion A cloud is the nearest giant molecular cloud, and is located at about 450 pc from the Sun (Genzel & Stutzki 1989). Extensive observations of the cloud have been made in CO (J = 2-1) (Sakamoto et al. 1994), ^{13}CO (J = 1-0) (Bally et al. 1987; Nagahama et al. 1998), CS (J = 1-0) (Tatematsu et al. 1993) and CS (J = 2-1) (Tatematsu et al. 1998). These observations have revealed that numerous dense cores, some of which are the birthplaces of new stars, are distributed throughout the cloud. The northern part of the Orion A cloud is known to be an active site of massive star formation. As a result, the cloud is illuminated by strong UV radiation from OB stars (G_0 is $\sim 10^5$ in the vicinity of Orion KL). By contrast, the central and southern parts of the Orion A cloud are more quiescent, and known as the L1641 dark cloud. Although a number of low mass protostars, T Tauri stars, and Hα emission-line stars are present, no massive stars are found there, and the UV radiation field is much weaker (G_0 $\sim$1-5). Therefore, the Orion A cloud is a good target for studying structure of a molecular cloud under various UV field strengths.

In contrast to the extensive studies of the molecular gas distribution, only a few mapping observations of CI have been reported toward small portions of the Orion A cloud. White & Padman (1991) and White & Sandell (1995) observed the Orion-KL region with a

$9''.8$ beam. Tauber et al. (1995) reported a $15''$ map of the Orion bright bar and Orion-S cloud. Tatematsu et al. (1999) explored the CI distribution in a part of the $\int$-shaped filament with a focal reducer system on the CSO. In this paper, we present the first large scale maps of CI and CO(J=3-2) covering the entire region of the Orion A cloud.

2. Observations

The CI($^3P_1-^3P_0$) and CO(J=3−2) data were taken between December 1998 and March 1999 using the Mt. Fuji submillimeter-wave telescope. The diameter of the main reflector is 1.2 m, corresponding to a HPBW of $2'.2$ and $3'.0$ at 492 GHz and 346 GHz, respectively. The telescope is enclosed in a space frame radome whose transmission efficiency is 0.8 at 492 GHz and 0.9 at 346 GHz. The pointing of the telescope was checked and corrected by observing 346 GHz continuum emission from the Sun and the Moon every month, and the pointing accuracy has been maintained within $20''$(rms) during the observing run. We used a 346/492 GHz dual band SIS mixer receiver in our observations. Typical system temperatures including the atmospheric attenuation were 500 K (DSB) at 346 GHz and 1500 K (SSB) at 492 GHz. The backend is a 1024 channel acousto-optical spectrometer which has a total bandwidth of 900 MHz and an effective spectral resolution of 1.6 MHz. We split the spectrometer into two halves, each with 450 MHz bandwidth, to allow simultaneous observations of the CI and CO(J=3-2) lines. Further details of the telescope will be described elsewhere (Sekimoto et al. 1999; Maezawa et al. 1999).

We observed using position switching, where the off-source position was at (α_{1950}, δ_{1950}) = ($05^{\rm h}28^{\rm m}46^{\rm s}.5, -05^\circ54'28".0$) for observations of the northern region and ($05^{\rm h}32^{\rm m}00^{\rm s}.0, -07^\circ18'00".0$) for the southern region, which were free of line emission to an rms noise level of 40 mK in the 1.6 MHz resolution. The intensity scale was calibrated using a chopper-wheel method. The moon efficiency including the radome loss is measured

to be 0.75 at 346 GHz and 0.72 at 492 GHz. We will present intensities in the main-beam temperature scale ($T_{\rm MB}$) throughout this paper. The line intensities were checked every 4 hours by observing Orion-KL. The overall relative uncertainty in the final intensity scale is estimated to be within 20 %. The zenith optical depth at 492 GHz ranged from 0.4 to 1.0 during the observations.

We have observed an $\sim$9 square degree area of the Orion A cloud with a grid spacing of $3'$. For most positions, the CI and CO(J=3-2) lines were observed simultaneously. Furthermore we have taken additional CI data with a grid spacing of $1'.5$ for an $\sim$0.9 square degree region around Orion-KL and L1641N. In total, 4613 CI spectra and 3087 CO(J=3-2) spectra were obtained. The on-source integration time ranged from 20 to 40 seconds per position and yielded typical rms noise temperatures of 0.5 K for CO(J=3-2) and 0.6 K for CI. In this letter we concentrate on the global distributions of CI and CO(J=3-2).

3. Overall distribution of CI and CO(J=3-2)

Figure 1a shows the intensity map for CI, integrated between 3 km s^{-1} and 13 km s^{-1}. CI emission is detected over almost the entire region of the Orion A cloud. The strongest CI emission is seen toward ($\Delta\alpha$, $\Delta\delta$) = ($-40''$, $-220''$) from Orion-KL ($05^{\rm h}32^{\rm m}46^{\rm s}.5, -05^\circ24'28''$), where the peak temperature is 14.0 K, and slightly weaker toward Orion-KL. This trend was also seen in the higher resolution beam of White & Sandell (1995). At Orion-KL the peak temperature is 9.1 K, the FWHM line width 4.4 km s^{-1}, and the peak LSR velocity 9.4 km s^{-1}, which agree closely with the results reported with a similar beam size by Phillips and Huggins (1981). In the CI map, the $\int$-shaped filament reported by Bally et al. (1987) is clearly seen. At the southern end of the $\int$-shaped filament, a large dark cloud called L1641N can be identified, which is known to be a formation site of a low-mass cluster (Hodapp & Deane 1993). The peak temperature of CI

ranges up to 7 K around this region. From the south of L1641N, a filamentary structure continues to the southern end of the cloud with an almost constant width of about 4.4 pc. The left edge of this filament forms a straight line, and the filament is broken into a number of smaller clumps. The CI intensity decreases toward the south with $T_{\rm MB} \leq 3$ K and $\Delta v \sim 2.5$ km s^{-1}, similar to values reported for HCL2 (Maezawa et al. 1999). The overall distribution of the CI emission closely resembles that of ^{13}CO(J=1-0) by Bally et al. (1987) with a similar ($1'.7$) beam to the CI observations.

Figure 1b shows the integrated intensity map for CO(J=3-2). The emission peaks at Ori-KL where its $T_{\rm MB}$=67.8 K and the line width Δv= 5.8 km s^{-1}. The line profile of CO(J=3-2) shows wing emission originating from the molecular outflow, which is not seen in the CI spectra. The CO(J=3-2) intensity drops sharply away from Ori-KL, and the $\int$-shaped filament is less clearly seen than in the CI map. In the central and southern parts of the cloud, the CO(J=3-2) intensity distribution is rather featureless compared to that of CI. Although the large scale distribution of CO(J=3-2) is similar to that of CI, the spatial extent is much larger. These features are probably due to a large optical depth in the CO(J=3-2) line. Toward the southern part of the Orion A cloud, $T_{\rm MB}$ of CO(J=3-2) is typically 3 K and $\Delta v \sim 3.0$ km s^{-1}, similar to that of the CI line.

4. CI/CO(J=3-2) intensity ratio

Figure 2a shows a map of the integrated intensity ratio of CI/CO(J=3-2). The ratio shows a gradient from north to south. Around the Orion-KL region the ratio is as low as 0.10, increasing to 0.29 in L1641N, and 1.2 at the southern end of the cloud. The total intensity ratio for the Orion A cloud is evaluated to be 0.37. This value is slightly lower than the value for the Galactic plane, 0.57, reduced to the intensity ratio from the values observed by the COBE satellite (Wright et al. 1991).

The CI optical depth has been suggested to be small or moderate (∼3) for a wide range of UV fields and densities (Zmuidzinas et al. 1988; Plume et al. 1999). By contrast the optical depth of CO(J=3-2) is expected to be much larger than that of CI. The CI/CO(J=3-2) ratio is sensitive to the optical depth of CI, if the CO(J=3-2) line is saturated and the excitation temperatures for both lines are similar. The observed gradient suggests that τ(CI) increases from the northern to the southern parts. The CI optical depth depends on the excitation temperature and on the column density (N(CI)). The gas kinetic temperature is known to have a spatial gradient, from 60 K at Orion-KL to ∼15 K at the southern end of L1641 (Tatematsu & Wilson 1998). If we assume the LTE condition, the CI optical depth increases by a factor of 6 from north to south with a fixed column density. Thus, the optical depth gradient is likely to reflect the temperature gradient, although a gradient in the CI /CO abundance ratio cannot be ruled out completely.

5. Correlation between CI and ^{13}CO(J=1-0)

Figure 2b shows a map of the integrated intensity ratio of CI/^{13}CO(J=1-0), where the ^{13}CO(J=1-0) data were taken from Bally et al. (1987). No systematic gradient is seen in this map. If we assume that the ^{13}CO(J=1-0) line is optically thin for the entire cloud, the CI/^{13}CO(J=1-0) integrated intensity ratio approximately expresses the optical depth ratio τ(CI)/τ(^{13}CO). Since the column density ratio N(CI)/N(CO) is proportional to the optical depth ratio at a given temperature, our result may suggest an almost uniform N(CI)/N(CO) ratio from north to south along the cloud regardless of the strength of the UV field. In order to confirm this, we derived the column densities of CI and CO under the LTE condition toward several representative positions as shown in Table 1, and find that the N(CI)/N(CO) ratio remains almost constant. However, the ratio along the ridge of the filament tends to be slightly lower than toward the edges. This trend is particularly clear in

the $\int$-shaped filament, and similar to that reported by Plume et al. (1999) for much smaller regions toward W3, NGC2024, S140, and Cep A.

Figure 2b also suggests that the integrated intensity of CI correlates well with that of ^{13}CO(J=1-0). A correlation between CI and ^{13}CO(J=2-1) intensity has previously been suggested by Tauber et al. (1995) and Tatematsu et al. (1999) toward small portions of the Orion A cloud. Our results show that this correlation holds over an almost entire region of the Orion A cloud. In order to investigate this in detail, we prepared a correlation diagram by integrating the intensities over the 1 km s^{-1} velocity width for the whole Orion A cloud (Figure 3a) and the southern region of the cloud (Figure 3b). The ^{13}CO(J=1-0) data were smoothed to a $3'$ grid for comparison with our CI data. The CI intensity has an offset at zero intensity from ^{13}CO(J=1-0), and increases almost linearly as the ^{13}CO(J=1-0) intensity increases. We least-square fitted the following equations; $\int T_{\rm MB}({\rm C_I})dv = A \int T_{\rm MB}(^{13}{\rm CO}(J=1-0))dv + B$, where we used the data above the 3σ noise level for the ^{13}CO(J=1-0) in this analysis. The coefficients (A, B) are derived to be (0.55$\pm$0.02, 0.87$\pm$0.04 K km s^{-1}) and (0.46$\pm$0.03, 0.92$\pm$0.06 K km s^{-1}), and the correlation coefficients are 0.82 and 0.80 for the whole cloud and southern regions, respectively. It should be noted that the CI emission tends to saturate for the larger ^{13}CO(J=1-0) intensities as seen in Figure 3b.

One explanation for these properties can be given in terms of a picture of a PDR. An almost identical CI distribution to that of ^{13}CO(J=1-0) could not easily be explained by homogeneous PDR models (e.g. Tielens and Hollenbach 1985). Taking this into account, we will assume that the cloud consists of a numerous small clumps, which are exposed to the external UV radiation. In a small clump with low visual extinction, all the CO is destroyed and only CI exists (Monteiro 1991). This may be the reason why the offset in the CI intensity is seen. The H_2 column density of such a clump is estimated from the B

constants to be $\sim 1 \times 10^{21}$ cm^{-2}, where the CI abundance is assumed to be 10^{-4} (Suzuki et al. 1992). This corresponds to a visual extinction $Av \sim 1$, which agrees with the depth of the CI layers in PDR models (e.g. Köster et al 1994; Spaans 1996). As the clump size increases, CO can exist in the central part of the clump. For larger clumps, the size of the CO core increases, and CI exists only near the clump surface. Therefore the CI emission tends to saturate for larger ^{13}CO(J=1-0) intensities.

If the above picture based on the PDR model is correct, the N(CI)/N(CO) ratio should depend on the size distribution of clumps as well as the UV field intensity. It is therefore curious that the N(CI)/N(CO) ratio shows no such systematic gradient from the northern to the southern part of the Orion A cloud. Considering this fact, the possibility that CI co-exists with CO in the deep interior of the cloud should also be considered seriously. Evolutionary models (Suzuki et al. 1992) and chemical bi-stability models (Le Bourlot et al. 1993) may be potential candidates. Further observations including the CI ($^3P_2 - ^3P_1$) line are necessary to characterize physical conditions of the CI emitting regions, which will be a key to solve the above problem.

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Fig. 1.— Integrated intensity of (a) CI ($^3P_1$–$^3P_0$) and (b) CO(J=3-2) observed toward the Orion A cloud, over the range 3 to 13 km s^{-1}. The solid lines enclose the observed region. The contour levels for CI are from 6 - 39 K km s^{-1} with intervals of 3 K km s^{-1}. The contour levels for CO(J=3-2) are 6, 12, 18, 24, 30, 39, 48, 60, 90, 120, 150, 210, 270 and 330 K km s^{-1}. Spectra observed at offset positions of (0, 0) and (15′, −60′) are also shown in each figure, where (0,0) corresponds to the central position $(\alpha,\, \delta)_{1950} = (05^{\rm h}32^{\rm m}46^{\rm s}.5, -05^\circ24'28'')$.

Fig. 2.— (a) Ratio of $\int T_{\rm MB}({\rm C_I})dv / \int T_{\rm MB}({\rm CO}(J=3-2))dv$. The contour levels range from 0.1 to 0.9 with intervals of 0.2. (b) Ratio of $\int T_{\rm MB}({\rm C_I})dv / \int T_{\rm MB}(^{13}{\rm CO}(J=1-0))dv$. The contour levels range from 0.3 to 0.9 with intervals of 0.2. The ^{13}CO(J=1-0) data was obtained from Bally et al. (1987). The velocity range integrated was from 3 to 13 km s^{-1} for all lines.

Fig. 3.— The intensities of CI integrated over 1 km s^{-1} bins running from 3 to 13 km s^{-1} are plotted against those of ^{13}CO(J=1-0). The ^{13}CO(J=1-0) data is obtained from Bally et al. (1987). The dashed lines show 3 σ levels. The thick solid lines denote linear fits to the data. The data correspond to (a) the whole region of the Orion A cloud, (b) the L1641S region (below declination -7.4°).

Table 1: Typical line parameters of CI and CO(J=3-2) and column densities of CI.

Source	Position	$T_{\rm MB}$ K		Δv km s^{-1}		$\int T_{\rm MB} dv$ K km s^{-1}		$T_{\rm ex}$[b] K	τ(CI)	N(CI) cm^{-2} $\times 10^{17}$	N(CO)[c] cm^{-2} $\times 10^{17}$	N(CI)/N(CO)
	$(\Delta\alpha,\, \Delta\delta)$[a]	CI	CO	CI	CO	CI	CO					
Orion KL	(0, 0)	9.1	67.8	4.4	5.8	46	475	65.0	0.2	6.2	123	0.05
L1641-N	$(15', -60')$	7.2	15.0	3.3	5.0	25	85	21.6	0.9	3.2	31	0.10
L1641-C	$(51', -102')$	5.4	6.0	2.2	3.7	14.1	25	15.9	1.5	2.1	9.8	0.21
L1641-S4	$(90', -165')$	3.6	3.8	3.2	2.8	13.8	11.4	16.0	0.7	2.0	14.4	0.14

[a]Offsets are relative to the central position $(\alpha,\, \delta)_{1950} = (05^{\rm h}32^{\rm m}46^{\rm s}.5, -05^\circ 24' 28'')$.

[b]Taken from Nagahama et al. (1998). $T_{\rm ex}$ for Orion KL is taken from Fig. 5 and for other positions from Table 2.

[c]The column density of CO is calculated from the ^{13}CO(J=1-0) data (Bally et al. 1987) assuming that CO/^{13}CO is 60 (Langer & Penzias 1993).